

Inducement and suppression of Coulomb effects in elastic 2D-2D electron tunnelling in a quantizing magnetic field

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Abstract

Tunnelling between two-dimensional electron systems has been studied in the magnetic field perpendicular to the systems planes. The satellite conductance peaks of the main resonance have been observed due to the electron tunnelling assisted by the elastic scattering on impurities in the barrier layer. These peaks are shown to shift to the higher voltage due to the Coulomb pseudogap in the intermediate fields. In the high magnetic fields the pseudogap shift is disappeared.

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Introduction

Coherent 2D-2D tunnelling is well known to have a resonance when subband energies E_{01} and E_{02} coincide in both two-dimensional electron systems (2DESs). Quantizing a lateral motion of electrons a normal magnetic field sharpens the coherent resonance and produces a series of satellite resonances originated from tunnelling between Landau levels (LL) with different numbers assisted the elastic scattering on impurities [1]. The condition of the elastic 2D-2D tunnelling is the following: $E_{01} - E_{02} = k\hbar\omega_c$. Here k is an integer number, ω_c is the cyclotron frequency. In other words in tunnel spectra the nearest satellites are separated by a voltage interval $V_c = \hbar\omega_c/e$. This single particle picture ignores many-body effect such as the Coulomb pseudogap (CP) that provides an additional voltage shift of the coherent resonance [2]. The pseudogap is originated from relaxation processes induced by the tunnelling electrons. In other words the tunnelling electron should have an additional energy to spend it on the relaxation therefore tunnelling is suppressed at low energies. This scenario is valid while the tunnelling time is very short in compare with the relaxation times. The interesting question is what happens if the relaxation will take part in tunnelling of electrons. To clarify the question it is suitable to investigate processes providing peak features in the tunnel spectra. The features of the elastic 2D-2D tunnelling are such kind of features. Here the Coulomb effects is reported to be revealed and studied in elastic 2D-2D electron tunnelling. In particular an inducement and a suppression of the Coulomb effects have been observed in a quantizing magnetic field.

Experiment

The investigated tunnel diodes represented columns wet-etched in a single barrier heterostructure of GaAs/ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ /GaAs type. The barrier layer was of 20 nm thickness and doped with Si at the middle. Due to the donor ionization the 2DESs accumulate on both side of the tunnel barrier in the undoped spacer layers of 70 nm thickness. The resistance of the spacers was quite low in compare with the barrier one. This provided common Fermi levels in 2DESs and adjacent contact n^+ -GaAs regions. The potential profile of the heterostructure is shown in Figure 1. The symmetry of the structure is supposed to be a result of the dopants diffusion

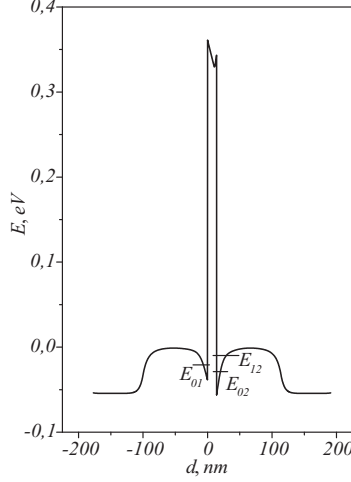


FIG. 1: The potential profile of the conductance-band bottom of the heterostructure under investigation with the quantum levels calculated self-consistently.

during the crystal growth. The conductance-voltage dependencies are shown in Figure 2 at different magnetic fields. At zero field the conductance peaks are the coherent resonant those. In particular the peak at $V_b = 3 \text{ mV}$ corresponds to the 0-0 resonance, i.e. $E_{01} = E_{02}$ and peak at $V_b = -12 \text{ mV}$ takes place when $E_{01} = E_{12}$. The electron concentrations were determined from magneto-oscillations of the tunnel current at low bias voltages and from the voltage position of the current peak at zero magnetic field. They are $n_1 = 3 \times 10^{11} \text{ cm}^{-2}$ and $n_2 = 5 \times 10^{11} \text{ cm}^{-2}$ the mobilities can be also estimated as $\mu_{1,2} \approx 50000 \text{ cm}^2/\text{Vs}$ [3]. The I-V curves of the tunnel diodes demonstrate a nonmonotonous magnetic dependence of the coherent-resonance position. The voltage dependencies of the tunnel conductance have pronounced satellite resonances or the conductance peaks shown in Figure 2. The satellite peaks also have nonmonotonous magnetic dependencies resembled the coherent resonance one (see Fig. 2).

Discussion

The triangles in Figure 2 follow the coherent peak position. The circles show the expected values for the first satellite peaks separated from coherent one at $V_{\pm s} = \pm \hbar\omega_c/e$. One can see that the expected positions are in quite good agreement with experimental ones at the positive voltage polarity (filled circles in Fig. 2) and in disagreement with those at negative polarity (empty circles in Fig. 2) at least for the magnetic field range $B \in (6 \text{ T}; 11 \text{ T})$. It

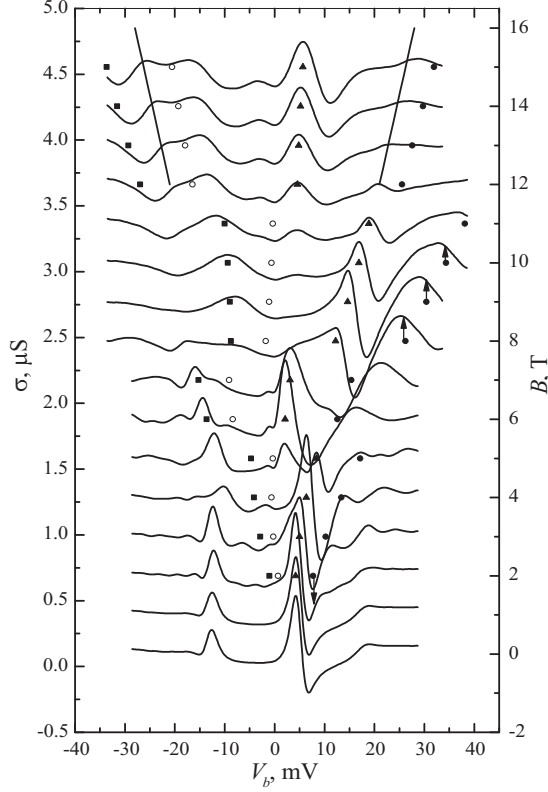


FIG. 2: Tunnel conductance-voltage dependencies at different magnetic fields in combination with the peaks positions magnetic dependencies. The curves are shifted to correspond magnetic field scale B , i.e. with step being proportional to the field that.

is interesting to note that the deviation can be cancelled with an additional voltage shift depended upon magnetic field. So if one supposes $V_{-s} \approx -1.5\hbar\omega_c/e$ the data coincidence will be better (see. squares at the negative voltage in Fig. 2). Such shift can be explained by the CP. In this case the positive satellite shifts together with the coherent peak and the energetic interval between them remains the same $eV_{+s} = \hbar\omega_c$. As for the negative satellite it is experienced the reverse shift and the energetic distance is increased on the double value of the CP $eV_{-s} = -\hbar\omega_c - 2\Delta_C$. The value of the CP can be estimated from the splitted coherent peak at very high magnetic fields. At these fields both 2DEs have the only one populated LL. Under this ultraquantum limit the resonant voltage should be zero [3]. In this case deviation originates only from the CP. Hence one can easy estimate the CP as a value of the deviation, i.e. $\Delta_C \approx 0.3\hbar\omega_c$. Thus one can justify the large value of V_{-s} . The next interesting feature appears at high magnetic fields $B > 11$ T where both the empty circles and the squares have lack to describe the satellite peaks positions. Moreover each peak has

splitted on a strongly and a weakly field depended ones. The strongly field-depended peaks follow to the cyclotron lines, i.e. $eV_{\pm p} = \pm \hbar\omega_c$ (see solid lines in Fig. 2). They can be considered as elastic satellites without the CP shift. The weakly depended peaks can be assigned to resonant tunnelling between the ground and the first excited subbands. Thus we can interpret the experimental data as a suppression of the CP effect on elastic peaks. Such suppression can be expected because, when the LL energy exceeds the first excited subband one, the intensive inter-subband scattering can decrease an electron life-time on the LL, i.e. the relaxations becomes faster, and thus decrease the role of the Coulomb effects.

Conclusions

The Coulomb pseudogap has been found to cause an additional voltage shift of the conductance peaks originated from 2D-2D tunnelling assisted by the elastic scattering. The disappearance of the shift has been also observed in the strong field when $\hbar\omega_c > E_{12} - E_{02}$ (see Fig. 1). The appearance of the CP effects means that elastic tunnelling is still quite fast in compare with lateral relaxation. The effect disappearance takes place probably due to the additional relaxation process, i.e. inter-subband scattering, becomes significant.

Acknowledgments

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